DESIGN OF A PLANAR WALKING MACHINE THAT INTEGRATES MECHANICAL AND CONTROL DESIGN APPROACHES

A Thesis

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By

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ABSTRACT

In the past 35 years, significant research has been devoted to understanding biped locomotion. However, a sizable number of the prototypes developed thus far have been limited to static or quasi-static gaits, and lack the ability to walk dynamically. This inherent inability to walk dynamically leads to walking cycles that are generally quite energetically inefficient. A large part of these inefficiencies are due to complex mechanical designs that lack a dynamic control design that compliment each other.

This thesis presents a design approach that integrates both the controller and mechanical design by designing and building a walking machine that will be used as an experimental platform to validate gait control algorithms that induce dynamic walking. Through experimental analysis, using the constructed walking machine, a standard framework can be developed that relates both the mechanical and controller design systematically. Once assembled, the mechanical integrity of the machine will be studied during initial experimentation and design changes will be made to improve its robustness. This final framework will allow future biped prototypes of different morphologies to perform stable, energy efficient walking cycles.

To all my friends and family who have supported
me throughout my academic endeavors.

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TABLE OF CONTENTS

ABSTRACT ii
PUBLICATIONS v
FIELDS OF STUDY v

Chapter 1: Introduction …….. 1
1.1 Background …….. 1
1.1.1 Phases of a Walking Cycle …….. 1
1.1.2 Static vs. Dynamic Walking Cycles …….. 2
1.1.3 Quantifying Gait Efficiency …….. 2
1.2 Current Biped Design Approaches …….. 3
1.2.1 Anthropomorphic Designs …….. 3
1.2.2 Vertical Hoppers …….. 4
1.2.3 Passive Walkers …….. 5
1.2.4 Walking Machines …….. 6
1.3 Project Motivation …….. 7
1.4 Design Approach …….. 8

Chapter 2: Drive System and Sensing Components …….. 12
2.1 Drive Components …….. 12
2.1.1 Motor and Gearhead Selection …….. 12
2.1.2 Cable Drive System …….. 13
2.2 Sensor Components …….. 16
2.2.1 Encoders …….. 16
2.2.2 Limit Switches …….. 17
2.2.3 Load Cells …….. 18

Chapter 3: Mechanical Design …….. 19
3.1 Body Design …….. 19
3.2 Hip Design …….. 22
3.3 Knee Design …….. 23
3.4 Foot Design …….. 24
3.5 Leg Design …….. 25
3.6 Final Design …….. 26

Chapter 4: Experimental Setup …….. 28
4.1 Platform Cart …….. 28
4.1.1 Opal RT System …….. 29
4.1.2 Breakout Boxes …….. 29
4.1.3 Power System …….. 29

4.2 Desktop PC ………………………………………………………………….. 29

Chapter 5: Design Complications ……………………………………………………. 30
5.1 Encoders ……………………………………………………………….... 30
5.2 Drive Pulleys …………………………………………………………… 31
5.3 Cabling …………………………………………………………………. 32
5.4 Body Inserts ……………………………………………………………. 33
5.5 Feet …………………………………………………………………….. 33
5.6 Wiring ………………………………………………………………….. 35
5.7 Opal RT System ……………………………………………………….... 37
5.8 Motor/Gearhead Selection ……………………………………………... 38

LIST OF TABLES

Table 3.1. Description of numbered items in Fig. 3.1 …………………………….. 20
Table 3.2 Description of numbered items in Fig. 3.4 ……………………………... 22
Table 3.3 Description of numbered items in Fig. 3.3 ……………………………... 23
Table 3.4 Description of numbered items in Fig. 3.4 ……………………………... 24
Table 3.5 Description of numbered items in Fig. 3.7 ……………………………... 26
Table 3.6 Physical properties of BIRT ……………………………………………. 27

LIST OF FIGURES

Figure 1.1 Double and single support phases for a simple, planar biped …………. 1
Figure 1.2 Support polygon, ……………………………………………………….. 2
Figure 1.3 ASIMO and QRIO ……………………………………………………. 4
Figure 1.4 Raibert's one legged vertical hopper …………………………………... 5
Figure 1.5 McGeer's passive walker Dynamite …………………………………… 6
Figure 1.6 Spring Flamingo ……………………………………………………….. 7
Figure 1.7 RABBIT ……………………………………………………………….. 8
Figure 1.8 BIRT ……………………………………………………………………. 9

Figure 2.1 Drive pulley cable design ……………………………………………... 14
Figure 2.2 Idler pulley design …………………………………………………….. 15
Figure 2.3 Gurley R112 rotary incremental encoder ……………….…………….. 17

Figure 3.1 Solid model of body assembly ………………………………………… 19
Figure 3.2 Motor layout in body as seen from the top ……..……………………... 20
Figure 3.3 Exploded view of outside body insert …………………………………. 21
Figure 3.4 Solid model of outside and center hip assembly ………………………. 22
Figure 3.5 Solid model of knee assembly …………………………………………23
Figure 3.6 Solid model of outside foot assembly …………………………………. 24
Figure 3.7 Solid model of leg assembly ……………………………………………26
Figure 3.8 Solid model of BIRT …………………………………………………... 27

Figure 4.1 Platform cart …………………………………………………………… 28

Figure 5.1 Hip encoder mounts …………………………………………………… 31
Figure 5.2 Turned down fasteners for feet …………………………………………34
Figure 5.3 Modified foot stabilization system design …………………………….. 35
Figure 5.4 Amphenol connector mounting plate ………………………………….. 37
Figure 5.5 Capacitors across motor amps to reduce crosstalk …………………….. 37

CHAPTER 1

INTRODUCTION

1.1 Background

1.1.1 Phases of a Walking Cycle

A single walking cycle consists of two phases. For the purposes of this thesis, these two phases will be defined as the double and single support phases. The double support phase occurs when there are two legs in contact with the ground. The single support phase occurs when there is only one leg in contact with the ground. The beginning of a walking cycle can start from either the double or single support phase, but each phase must succeed the other. A depiction of the double and single support phases for a simple, planar biped is shown in Fig. 1.1.

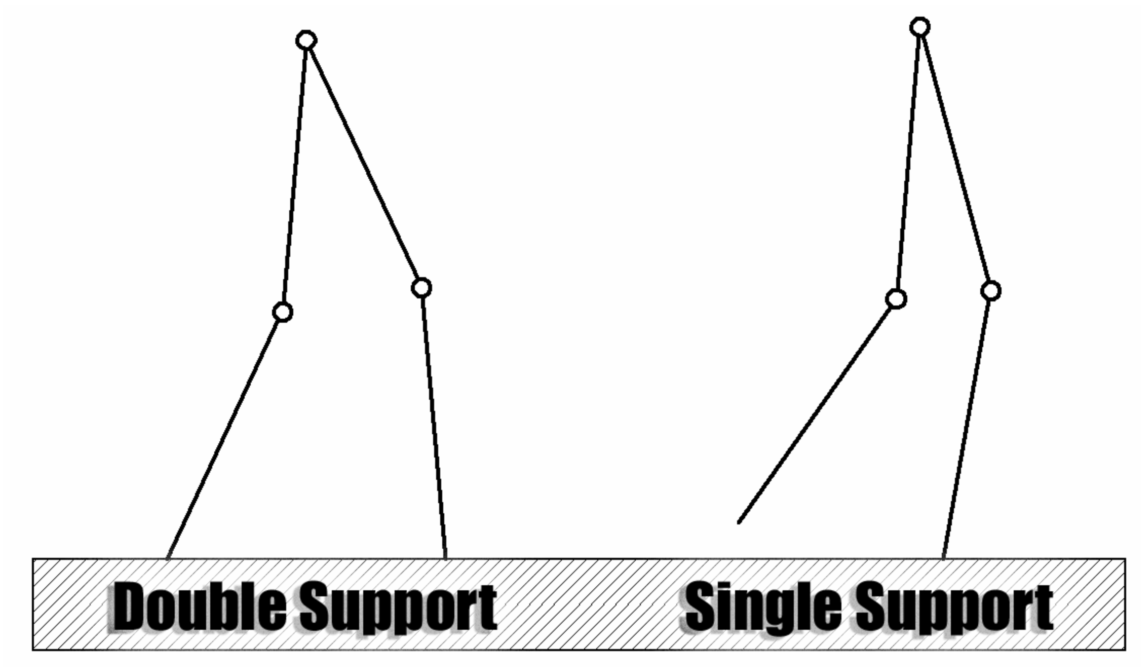

Figure 1.1 Double and single support phases for a simple, planar biped

1.1.2 Static vs. Dynamic Walking Cycles

The stability of a biped is directly related to the location of its center of mass inside its support polygon. The support polygon of a biped is the area whose perimeter corresponds to the footprint outlined by the extents of its feet; see Fig. 1.2. Statically stable walking cycles occur when the biped's center of mass remains inside its support polygon. A dynamic walking cycle occurs when the center of mass reaches or exceeds the boundary of its support polygon, which results in a gait that is not statically stable. Therefore, the size of a biped's feet directly affects the stability characteristics of its walking gaits.

Figure 1.2 Support polygon

1.1.3 Quantifying Gait Efficiency

Based on the findings of Gabrielli and VonKarman [1], gait efficiency can be defined as the ratio of the consumed power P to the product of the gross weight W and the velocity V, as shown in Eq. 1.1. This equation refers to efficiency and its relation to power consumption. Therefore, to achieve an efficiency of 100 percent all the consumed power must contribute directly to the forward velocity of the biped.

$$\in = \frac{P}{WV} \qquad [1.1]$$

1.2 Current Biped Design Approaches

Research over the past three decades has been dedicated to a number of design approaches, including anthropomorphic designs, vertical hoppers, passive walkers, and planar walking machines. All of these fields of research have made significant impacts in the field of biped locomotion. This section discusses these different design approaches, and their respective contributions to the motivation for this project.

1.2.1 Anthropomorphic Designs

In 1973, Waseda University introduced the world to WABOT-1 [2], the first full-scale humanoid robot. Since then, companies such as the Honda Motor Company and Sony Corporation have led the way towards a new wave of robots marked by the recent unveilings of ASIMO [3] by Honda and QRIO [4] by Sony, see Fig. 1.3. Both of these bipeds are products of decades of research and numerous prototypes.

One of the most stunning facets of ASIMO and QRIO is their smooth control, and seemingly effortless motions. These motions are achieved by recording joint trajectories of humans performing the desired motion in an effort to identify stable motions. Based on the recorded motions, a time-based trajectory was predetermined for each joint. By moving and tracking each joint, feedback controls are used to insure that the predetermined trajectories of each joint are achieved. This control approach is known as *trajectory tracking* and is used on both of these bipeds with very convincing and impressive results.

While the movements produced using trajectory tracking control are very impressive, it does not bring us closer to understanding human locomotion or what parameters are most influential in optimizing gait efficiency. This approach does not feature an intelligent control design that can react to a changing and unpredictable environment on the fly. Additionally, these prototypes have very complex mechanical designs making it difficult to study new control approaches.

Figure 1.3 ASIMO and QRIO

1.2.2 Vertical Hoppers

Marc Raibert [5] demonstrated in the late 80's that steady-state running gaits could be accomplished using a few simple decoupled control laws; see Fig. 1.4. This research laid the groundwork for a theory applicable to running robots. Using an event-by-event control approach, the control for each succeeding step is based on the result of the previous step by employing simple laws of physics. Raibert's control approach is extremely effective, but the question remained how can this approach be adapted to create smooth, time-continuous walking motions, particularly under non-steady state conditions.

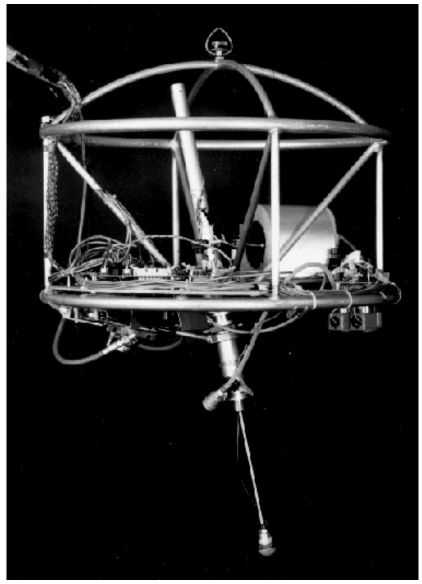

Figure 1.4 Raibert's one legged vertical hopper

1.2.3 Passive Walkers

Tad McGeer [6] approached the task of understanding and explaining the passive dynamics of human walking gaits in the late 80's with the development of Dynamite. Dynamite is a 2-D passive walker with knees and is an improvement based on the result of previous research conducted with a 2-D straight-legged walker; see Fig. 1.5. By the early 90's, McGeer demonstrated that passive machines were capable of locomotion at various speeds, down hills, in two dimensions, and over unevenly spaced footholds. The results of these experiments suggest exciting possibilities regarding the design a walking machine and that intelligent mechanical design could have an invaluable effect on the performance of such a machine.

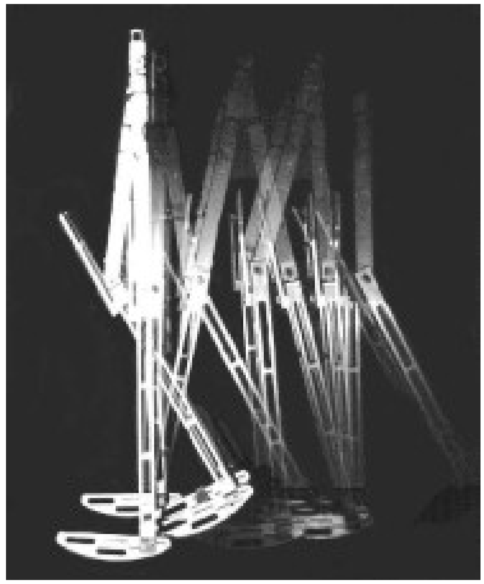
Figure 1.5 McGeer's passive walker Dynamite

1.2.4 Walking Machines

In the late 90's, Jerry Pratt [7] developed Spring Flamingo, the most impressive planar walking machine to date, which made use of a unique control approach known as virtual model control (VMC), see Fig. 1.6. Spring Flamingo was developed to serve as an experimental platform for implementing various control algorithms and force control actuation techniques. The control approach implemented on Spring Flamingo was similar to that developed by Raibert in that it used a few simple rules. However, Pratt was the first to successfully implement VMC in walking gaits.

Figure 1.6 Spring Flamingo

The distinct advantage of VMC is that it enabled Pratt to quickly implement walking gaits using calculations not much more complex than the Jacobian of the robot's configuration. Three simple virtual components were used: height, pitch and forward speed. With just these three simple virtual components, walking proved to be easily accomplished.

However, problems were encountered when implementing VMC control on Spring Flamingo because it needed to be tuned by hand. This problem was remedied by adding a new, fourth, virtual component for adaptation, which automatically tuned the machine. While the Spring Flamingo project proved to be a huge success, the issue of non-steady-state walking, including changes in direction and speed, was not addressed.

A walking machine that does address the problem of non-steady state walking is RABBIT [8]. RABBIT was developed in France in the late 90's (Fig. 1.7). The high gain PI control approach implemented on RABBIT was developed by Eric Westervelt [9], and has proven to be more robust than the VMC approach implemented on Spring Flamingo. Using Westervelt's control approach, it is also believed that running gaits are possible, although it has not been validated experimentally at this point.

Figure 1.7 RABBIT

1.3 Project Motivation

The goal of this project is to design and build a planar walking machine that will be used to validate various control algorithms that attempt to maximize walking gait efficiency. Similar to Spring Flamingo, whose mechanical design was based on principles demonstrated by McGeer's passive walkers and whose control design was based on principles demonstrated by Raibert's vertical hoppers, the biped design in this project integrates mechanical and control designs.

The control approach of this new walking machine will be based on that developed by Westervelt and implemented on RABBIT. The mechanical design approach will avoid the redundancies seen in anthropomorphic bipeds such as ASMIO and QRIO that only further complicate the control design with no added benefit to the gait efficiency. This biped design will also serve as a platform for future experiments including testing control algorithms that employ added compliance.

1.4 Design Approach

BIRT, the BI-ped R-obot with T-hree legs, is a planar biped and was developed in the Locomotion and Biomechanics Lab at The Ohio State University between the fall of

2003 and 2004, see Fig. 1.8. The design of this machine was constrained to one plane in order to simplify the machine, since most of natural walking motions occur in the sagittal plane. BIRT is the result of a design approach that integrated the mechanical design and control design. This section contains an explanation of the conceptual design approach taken before the initial design began.

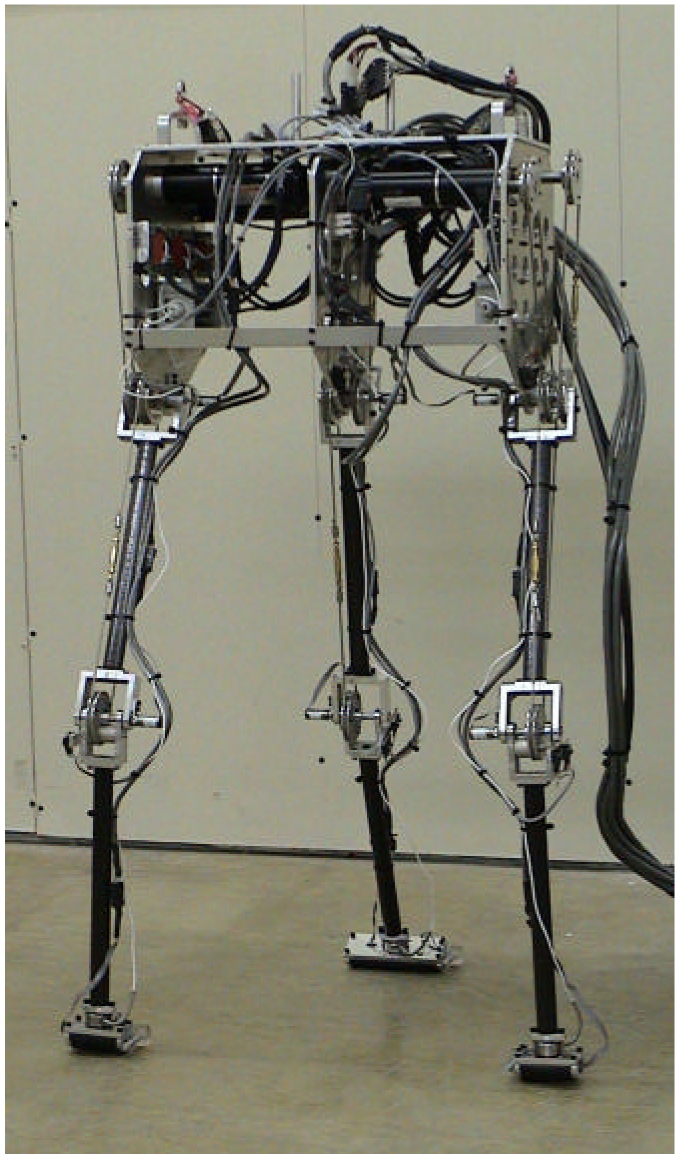

Figure 1.8 BIRT

Designing a walking machine is a very complicated task. The design of BIRT was driven by the ultimate goal of building a machine that takes a simplified mechanical design further by exploiting the control design, allowing the experimenters to directly study the effects of an informed control design on walking gaits. Adding numerous degrees of freedom to the machine is believed to be unnecessary to perform energetically efficient walking gaits and further complicates the control design.

Based on the idea of a simplified mechanical design approach, the biomechanical structure of a human or biped organism was not mimicked, as seen previously in anthropomorphic prototypes. For this reason, the selected design features a total of four single degree of freedom joints: left hip, right hip, left knee and right knee. The feet were modeled with point contacts to simplify the control design. Using this design approach enables one to force a dynamic walking cycle by eliminating the static region of the biped's support polygon during the single support phase. Further, since the feet are un-actuated, a rolling contact was utilized.

Another feature of the mechanical design strategy is a third leg and provides stability in the frontal plane. The two outside legs are slaved together through control. This contrasts some previous planar biped designs that feature a boom arm to provide stability. A third leg allows for the machine to be easily transported to offsite demonstrations. Designs featuring a boom arm are rather cumbersome and do not easily allow one to transport the machine. Additionally, having a third leg provides experimental flexibility and the possibility of skid steering to achieve turns.

While a third leg could have been slaved to the opposite outside leg mechanically through a rigid link, such a design would result in larger leg inertias. Increasing the inertias of the outside legs was unfavorable since it would lead to larger required torques at the joints. Following this line of thinking, the mechanical design was based around the design approach of concentrating the majority of the mass of the machine off the legs and within the body.

It has been demonstrated in previous biped prototypes that the majority of their mass is in the actuation system. BIRT's actuators are brushless DC motors, instead of other means of actuation such as hydraulic or pneumatic systems. Brushless DC motors were the natural choice for the actuation system since hydraulic systems require heavy pumps and pneumatic systems have too much compliance.

This thesis outlines the procedure taken while designing BIRT's mechanical system. The following chapters include: selection of drive system and sensing components, solid modeling of the mechanical system and a summary design complications encountered during preliminary experiments. Addressing the design complications experienced during experimentation will aid in the design of more robust biped prototypes. It is understood that complicated machines including ASIMO and QRIO as well as simpler machines such as passive walkers chase one common theme and that is excellent control cannot compensate for deficiencies in a machines mechanical design. At the same time a more robust mechanical design can only make implementing control easier. For this reason it is important to understand what makes a biped's design robust.

CHAPTER 2

DRIVE SYSTEM AND SENSING COMPONENTS

2.1 Drive Components

Before beginning the mechanical design of the machine, several steps were taken; including specifying the drive and sensor components. As mentioned previously, it had already been determined during the conceptual design phase that the machine would have three legs and would be actuated using brushless DC motors. Following this stage of the design, the design of each subassembly of the machine could commence. These subassemblies include the body, hip, knees and feet.

2.1.1 Motor and Gearhead Selection

As stated previously, the selected means of actuation was brushless DC motors. After an extensive Internet search, it was determined that the Maxon[1] motor company offered the most extensive collection of high power density motor and gearhead options. Before selecting a motor and gearhead combination, it was first necessary to determine the required torque and speed characteristics of the actuation system.

To obtain these predicted torque and speed values, a design was created within the solid modeling software package SolidEdge. In SolidEdge, it is possible to specify a weight for each portion of the machine including the body, thigh (upper leg) and shank (lower leg). Since it was already determined that the design would have three legs, the center leg's thigh and shank were given mass properties twice that of the outside legs. It was also determined at this point in the design process that the machine would stand about one meter tall. The reason for this value was based on the fact that the machine should be small enough to transport to offsite demonstrations.

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[1] www.mpm.maxonmotor.com

Based on the inertia data and geometrical structure of this preliminary design, a simulation was completed in MATLAB. Simulations were performed for speeds up to 1.1 m/s and using the mass of a single outside leg, twice that for the center leg and with an added 3 kg mass applied to the torso. Using this simulation technique allowed for the mechanical and control design to be integrated. It was determined that the motor and gearhead combination should possess a stall torque of 22.5 N-m, and a no load speed of 50 rpm for the center leg. Using the simulation determined specifications, a comparative study of all the stock motors and gearheads offered by Maxon was conducted. It was important to look at the stock motor options since the lead-time would be significantly less, and reduce the time before components would arrive for assembly. Lower torque motor and gearhead options were investigated for the two outside legs. However, using different motors and gearheads for the outside legs did not offer a significant weight reduction and for this reason identical actuators were purchased for all the legs.

Based on the comparative study, it was determined that the best motor and gearhead option was the 118896 and 203120 respectively. The 203120 gearhead provides a speed reduction of 43:1. The stall torque and no load speed of this actuator setup are 21.8 N-m and 137.2 rpm, respectively. The no load speed was not considered a critical characteristic while selecting actuators and instead concentrated on matching torque requirements.

2.1.2 Cable Drive System

It was determined earlier that the motors would be located in the body of the machine in order to reduce the mass moment of inertia of the legs. Therefore, a means of transmission from the output shafts of the motors to the hip and knee joints was needed. Means of transmission considered included timing belts and cable drives. Disadvantages were found for each means of transmission. Timing belt pulleys were rather bulky and heavier than grooved pulleys. Grooved pulleys, however, are not a means of positive drive and can slip if large resistive torques are present, as would be experienced during walking. A comparative study was also completed to determine what stock pulley options existed from manufacturers. The results of this study were not favorable. It was determined that some means of positive drive reinforcement needed to be applied, and all the drive belt options available were rather large and difficult to incorporate into the design.

For this reason, it was determined that the best option for the drive pulleys was to have them custom fabricated. Since a timing belt pulley would be difficult to fabricate, using grooved pulleys seemed like a more favorable option. In order to alleviate the problems associated with cable slippage on grooved pulleys, a clamping system was integrated into the pulley design. See Fig. 2.1. Another consideration when designing the drive pulleys was the nominal diameter of the pulley. In earlier biped prototypes, such as MIT's Spring Flamingo [7], it was found that when using small cable diameters along with too small of a pulley diameter, problems were encountered with cable failure. For this reason, a nominal pulley diameter of 2 inches was used to avoid this problem. The final drive pulley design is shown in Fig. 2.1.

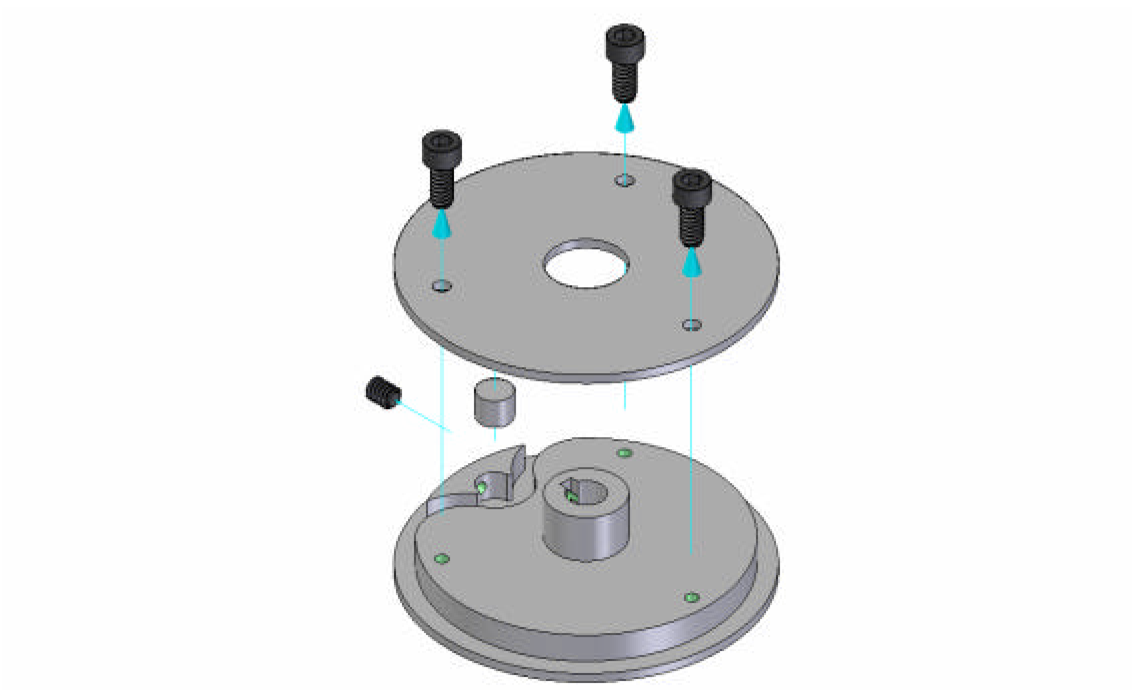

Figure 2.1 Drive pulley cable design

One of the key features of the drive pulley design is a cable clamping system, as seen in Fig. 2.1. The base of this part has a sine-wave-shaped groove machined into it. This groove allows for the cable to be recessed inside the pulley to accommodate a clamping system. The clamping system consists of a small cylinder that rests in a circular cutout to clamp down on the cable using a setscrew. This clamping system is an integral part to preventing the cable from slipping.

In order to transmit power to the knee joint, an idler pulley was used at the hip. In order to keep tension in the cable, the knee drive cable was wrapped once around the idler pulley at the hip, and then sent to the knee. While this knee cable drive system maintains tension in the cable, it does introduce a coupling effect in the knee drive system. No reasonable means for avoiding this coupling effect was found, and the experimenters believe that while it is not ideal, it can be accounted for in the control design of the walking machine. Ordinarily, it is desired to control the shank angle relative to the thigh but because the drive is coupled at the hip the shank angle is controlled relative to the body. In order to accommodate the wraps of cable around the idler pulley, a pulley had to machined. The idler pulley design is shown in Fig. 2.2.

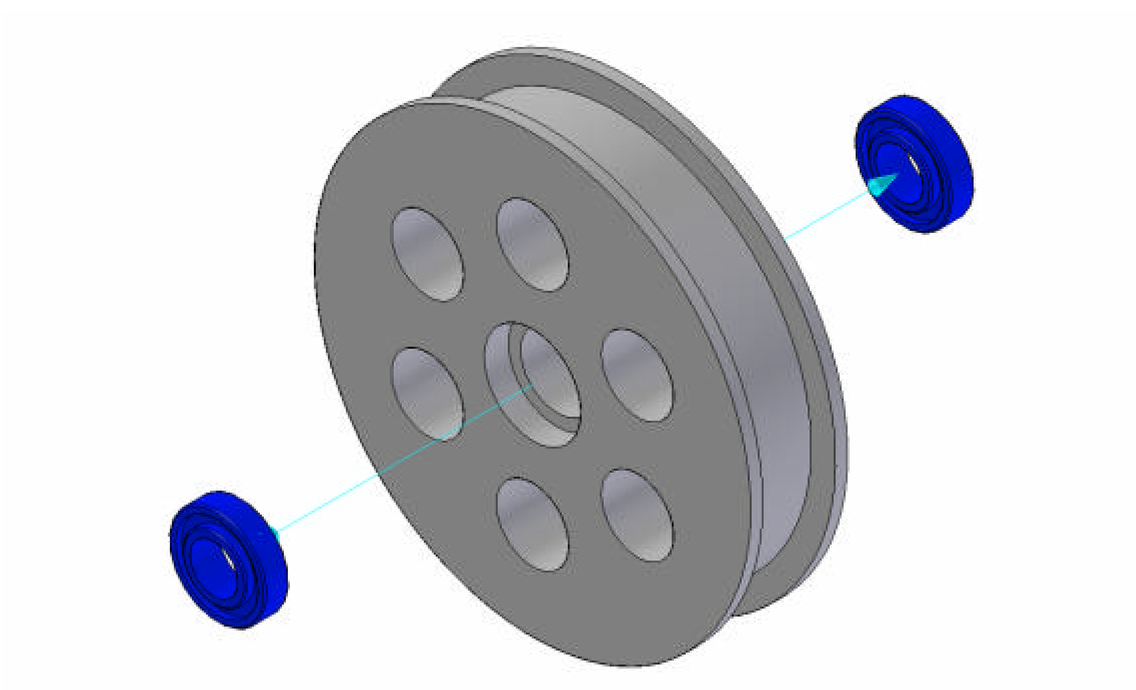

Figure 2.2 Idler pulley design

In order to reduce the weight of the idler pulley, holes are located on the face of the pulley in a circular pattern. Also displayed in the Fig. 2.2 are two ball bearings with extended inner races that were press fit in bores on either side of the pulley. The extended inner race ball bearings were purchased from Stock Drive[2] and were used to provide a gap between the idler, drive pulley and body plate insert at the hip.

Before the dimensions for the drive and idler pulleys could be finalized, the drive cable had to be selected. The drive cable was purchased from Carl Stahl Sava Industries, Inc[3]. Sava offers a number of different braid configurations, and since it was important that the cable not be too stiff, a braid pattern was selected based on this criteria. The selected cable has a 7x49 braid pattern, nylon coating with a diameter of 3/32 inches and a minimum breaking strength of 550 lbs.

Another aspect of the cable drive system to consider was a tensioning method. To introduce tension into the drive cabling, turnbuckles also purchased from Sava were used to connect the free cable ends. In addition to allowing a means for increasing cable tension, using turnbuckles also allows for the future addition of compliance in the drive system. Studying control design of compliant systems is a future goal of the experimenters, therefore turnbuckles are believed to be the best option and allow one to easily switch from a system with added compliance to a system without.

2.2 Sensor Components

A series of sensor components were located on BIRT including encoders, limit switches, and load cells provide feedback to the controller. All of these sensor components play an intricate role in the control design for BIRT.

2.2.1 Encoders

Rotary optical encoders were used for tracking joint and motor orientation. Encoders were located at both the motors and joints to account for compliance in the cable and future experiments involving springs placed inline with the cabling. When compliance is present in the drive system a difference in angular orientation will exist between the motors and joints. Having encoders at both these locations also allows for a tracking error calculation.

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[2] www.sdp-si.com
[3] www.savacable.com

The selected motor encoder was purchased from Maxon based on available options for the selected motor mentioned in section 2.1.1. The selected motor encoder (HP HEDL5540) has 500 counts per revolution and provides position feedback for the joint level control.

For joint tracking, R112 rotary incremental encoders were purchased from Gurley Precision Instruments[4], see Fig. 2.3. This encoder was selected based on its compact size, and high resolution. These encoders only weigh 15-grams and have a resolution up to 8,000 cycles per revolution and 32,000 counts per revolution after 4X quadrature decode.

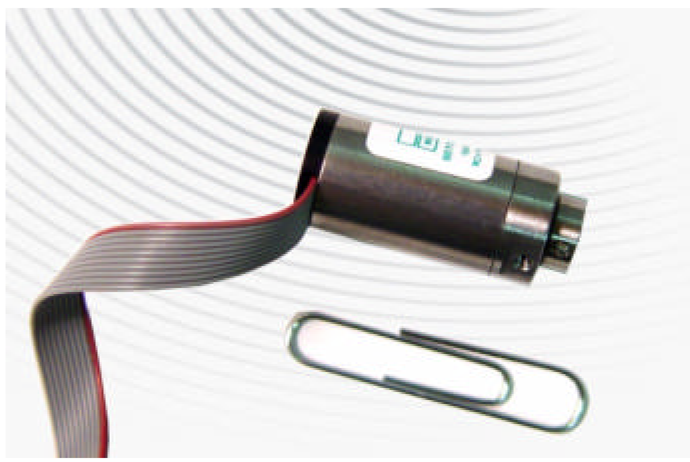


Figure 2.3 Gurley R112 rotary incremental encoder

2.2.2 Limit Switches

Limit switches were used as part of an emergency stop mechanism and were placed at both the hip and knee joints of BIRT. The switches are mounted to hard stops and are triggered when a joint angle of ±90° is reached. The limit switches were purchased from Digi-Key, and are basic hinge lever micro switches.

A circuit was designed to receive the signal from the limit switches using a series of IF/OR logic circuits. If any of the limit switches are triggered a signal is sent to the power supply that cuts the power to the system. This circuit is mounted in the body of BIRT, and by placing the board here decreases the number of wires from BIRT to the external power supplies and breakout boxes.

[4] www.gpi-encoders.com

2.2.3 Load Cells

Load cells were placed in each of the feet and used to detect the instant of ground impact. Amplifiers were purchased and placed within the body of the machine. The load cells and amplifiers were purchased form Sensotec[5], and have a max load rating of 100-lbs. This load rating was determined according to ground impact predictions. The weight of the biped was predicted to be roughly 30-lbs. It is understood that ground impacts would exceed the weight of the machine but believed to not exceed 100-lbs.

[5] www.sensotec.com

CHAPTER 3

MECHANICAL DESIGN

3.1 Body Design

The body of the biped contains the majority of the drive and sensing components. This is in part due to the desire to locate the majority of heavy components away from the swinging mass of the legs. It is also much easier from a design perspective to mount components to the plates of the body. A solid model of the body assembly is shown in Fig. 3.1, along with a description of each numbered item in Table 3.1.

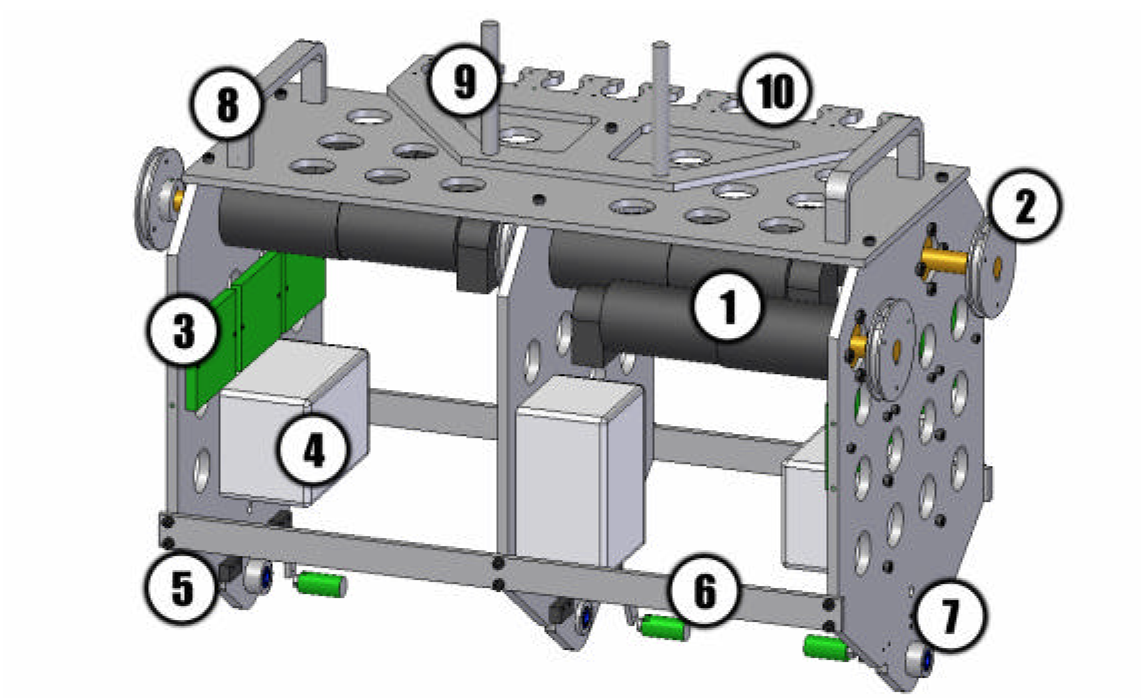


Figure 3.1 Solid model of body assembly

Table 3.1. Description of numbered items in Fig. 3.1

1: Brushless DC motor	2: Drive pulley
3: Motor amplifier	4: Load cell amplifier
5: Limit switch	6: Joint encoder
7: Body plate insert	8: Handle
9: Shaft support for additional weight	10: Connector mounting plate

The body support structure is constructed out of 6061-Aluminum. Three ¼-inch vertical body plates provide mounting for the motors, amplifiers, limit-switches, and encoders. A 3/16-inch plate that mounts to the top of the three body plates and two 3/16-in bars that run along the side of the body plates add rigidity to the structure. Two DC motors are mounted on each of the three vertical plates. The two motors that drive the center leg are located on opposite sides of the center body plate. The two outside vertical plates are identical, but are oriented in opposite directions. The location of each motor within the body is shown in Fig. 3.2

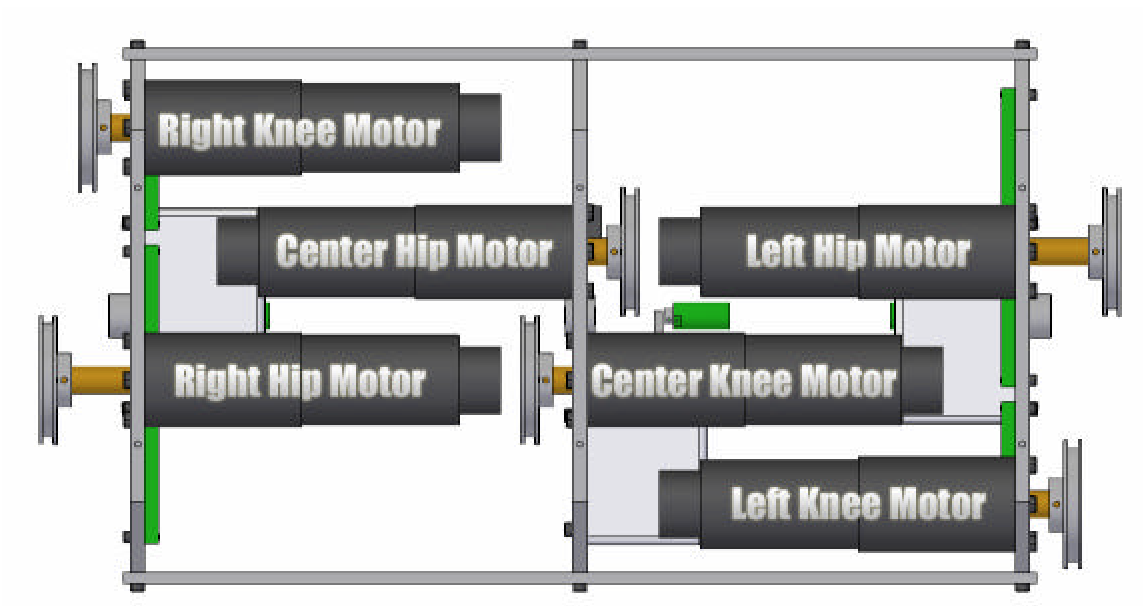


Figure 3.2 Motor layout in body as seen from the top

Three motor amplifiers are mounted on each of the two outside body plates. One load cell amplifier is mounted on each of the three body plates. Two limit-switches are mounted on each of the body plates near the hips. As stated previously, the limit switches are part of an emergency stop circuit. The emergency stop circuitry for the limit-switches is located on the rear portion of the center body plate (side furthers from viewer in Fig. 3.1). Three joint encoders are mounted near the hips on each of the three body plates, using encoder mounts fabricated out of aluminum sheet metal.

Three body inserts are press fit into each of the three vertical plates. See Fig. 3.3. The body insert consists of turned aluminum bar-stock with bores for ball bearings that are press fit into the insert, and accommodate the drive shaft of each hip. These inserts resist a bending moment applied to the body plates from the tension in the drive cables. The two outside body inserts are twice as long as the center body insert, since the bending moment at the center leg is less due to the drive cables for the hip and knee being located on opposite sides of the center vertical plate providing a balanced loading.

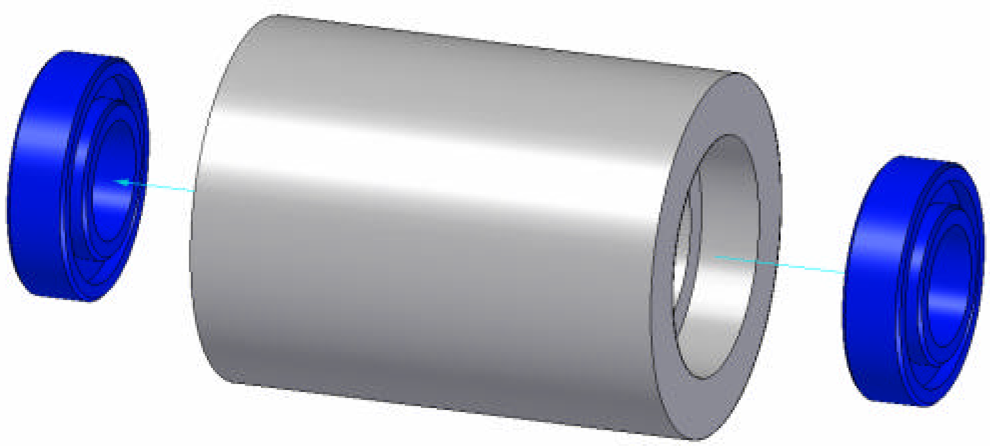


Figure 3.3 Exploded view of outside body insert

Two aluminum handles purchased from McMaster Carr are located on the top plate. These handles serve as an attachment point for the gantry system which BIRT is tethered to for hardware projection resulting from falling during experimentation. Two vertical support shafts are located on the top plate. These supports make it possible to add mass to the body of the biped, which will change the natural dynamics of BIRT and in order to mimic having an on board power system.

3.2 Hip Design

The main purpose of the hip assembly is to accommodate a drive and idler pulley. A motor, located in the body of the biped, drives the hip drive pulley. The idler pulley serves as a coupler between the drive motor, located in the body of the biped, and the knee drive pulley. A solid model of the hip assembly is shown in Fig. 3.4, along with a description of the numbered features in Table 3.2.

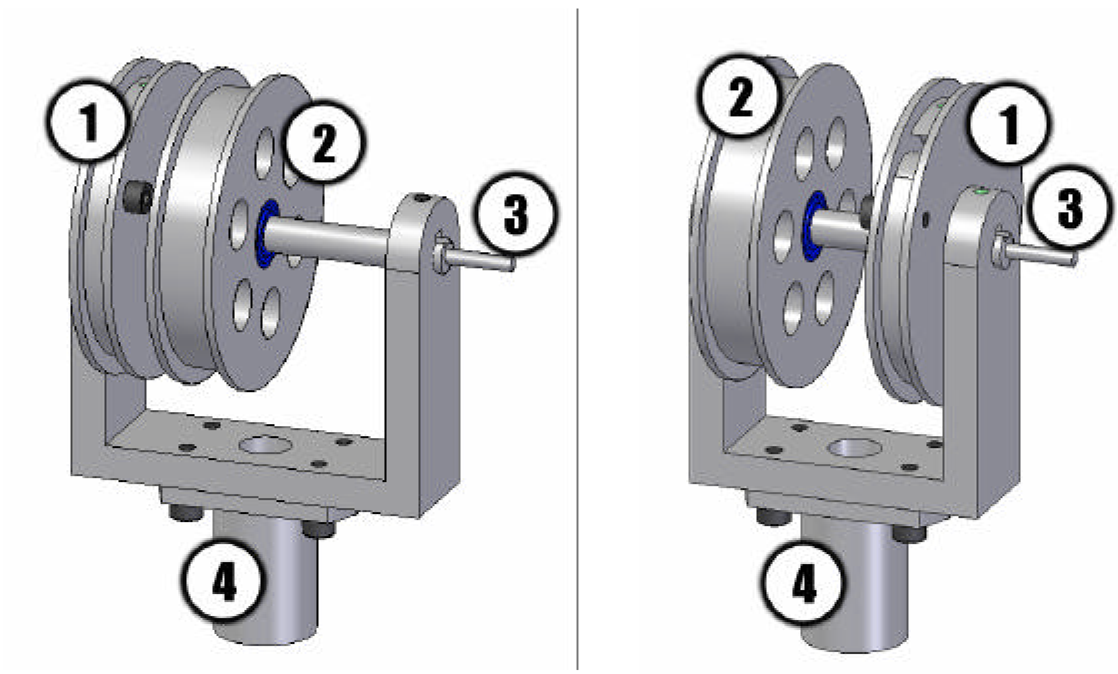


Figure 3.4 Solid model of outside and center hip assembly

Table 3.2 Description of numbered items in Fig. 3.4

1: Drive pulley	2: Idler pulley
3: Hip drive shaft	4: Leg plug

The construction and assembly of the drive and idler pulley assemblies are described in Chapter 2. The drive shaft of the hip is constrained axially with two setscrews located at the top of the U-bracket. These setscrews provide a clamping force on the keys located in keyways machined into the U-bracket, drive shaft, and drive pulleys. The last facet of the hip design is the leg plug. The leg plug is inserted into the carbon fiber tubing that serves as the thigh and attached with an adhesive Hysol 9430. The plug is then fastened to the U-bracket.

3.3 Knee Design

The main purpose of the knee assembly is to accommodate a drive pulley. Power is transmitted from the motor, located in the body, and drives the knee using a cable transmission. However, a number of other design considerations had to be made to accommodate limit switches, encoders and carbon fiber plugs. A solid model of the knee assembly is shown in Fig. 3.5, along with a description of the numbered features in Table 3.3.

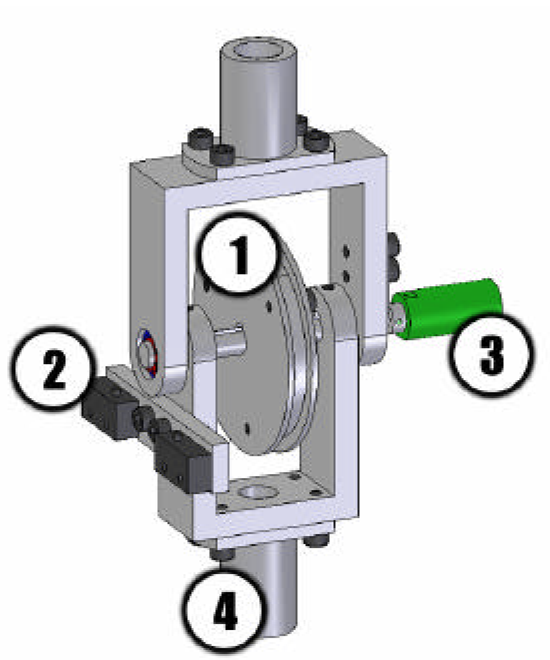


Figure 3.5 Solid model of knee assembly

Table 3.3 Description of numbered items in Fig. 3.3

1: Drive pulley	2: Limit switches
3: Joint encoder	4: Leg plug

The drive shaft of the knee is turned from bar stock to a diameter of ¼-inch and is constrained axially by two retaining rings. Two ball bearings are press-fit into the upper U-bracket, and aluminum spacers provide clearance from the lower U-bracket. The lower

U-bracket and drive shaft both have keyways machined in them and are constrained axially with two setscrews.

The limit switches are mounted on a bar attached to the lower U-bracket and when triggered, cuts the power supplied to BIRT. The bar also serves as a hard stop that limits the joints from exceeding ±90°. The joint encoder is mounted on the opposite side of the knee to the upper U-bracket with two fasteners. The manufacturer's flexible encoder mount is attached to the mounting bracket with a single fastener.

3.4 Foot Design

The main functions of the foot assembly are to detect the instant of ground impact and measure the angle between the ground and the shank when in contact with the ground. Load cells detect ground impacts, and the ground-to-shank angle is measured with an encoder. A solid model of foot assembly is shown in Fig. 3.6, along with a description of the numbered features in Table 3.4.

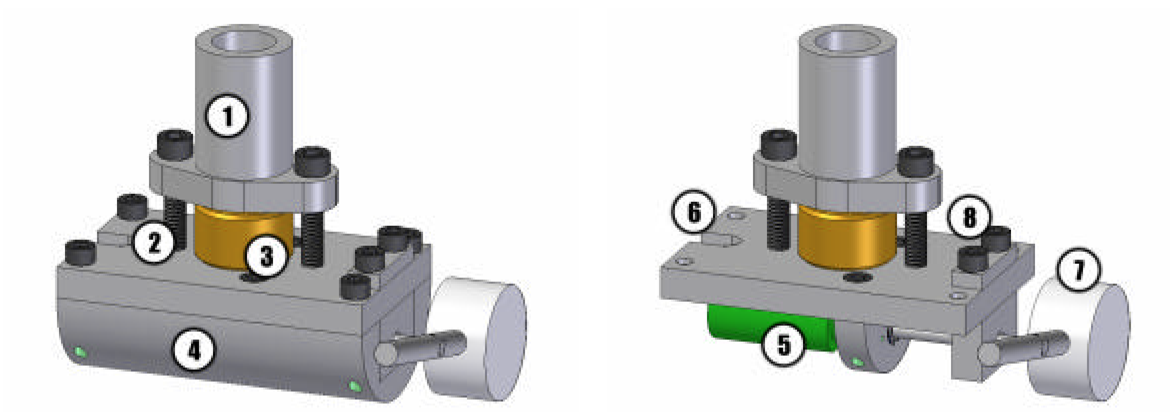


Figure 3.6 Solid model of outside foot assembly

Table 3.4 Description of numbered items in Fig. 3.4

1: Leg plug	2: Foot stabilization system
3: Load cell	4: Semi-cylindrical foot
5: Encoder	6: Encoder wire cutout
7: Ground angle pendulum	8: Pendulum restrictor clamp

The leg serves as part of the foot stabilization system in addition to joining the foot with the carbon fiber shank. Two threaded holes in the leg plug accept a fastener that has a clearance fit in a bore in the top plate of the foot. The purpose of the fasteners is to constrain the foot from rotating freely, while not affecting the load cell measurements.

As stated previously, the load cell serves as a ground impact sensor. A spring-loaded micro switch could have accomplished this same function. However, one of the goals of this design is to have the ability to record the magnitude of the ground impacts, which may be useful in the design of future biped prototypes.

The foot is semi-cylindrical in shape, which provides a continuously rolling contact. By designing a foot this shape, dynamic gaits are forced, due to the reduced size of the support polygon. Further, the center foot is twice as long as the outside feet so that the length of foot in contact with the ground during the single support phase is the same.

As stated previously, the encoder in the foot detects the angle between the ground and shank. It should be noted that most planar walking machines use a boom arm for stabilization in the frontal plane and an encoder between the boom arm and body of the biped then determines the torso angle. However, this design does not include a boom arm, and therefore, the torso angle is determined using the ground to shank angle along with the other joint angle measurements. The encoder is mounted to a shaft with setscrews, which is axially aligned with two ball bearings and constrained axially with two retaining rings. The purpose of the ground angle pendulum is to measure the ground-to-shank angle. The cylinder mounted to the pendulum shaft is constructed from turned nylon bar stock. The final part of the ground angle measurement system is a pendulum restrictor clamp. This clamp is used to fasten a rubber band that is wrapped around the pendulum shaft and offsets the pendulum from a vertical orientation to prevent the pendulum from bouncing off or turning the wrong direction during impact.

3.5 Leg Design

A solid model of a leg sections is shown in Fig. 3.7, along with a description of the numbered features in Table 3.5. The long cylindrical tube is carbon fiber tubing selected for the design based on its high strength-to-weight ratio. As mentioned previously, the leg plugs are adhered to the carbon fiber tubing using Hysol 9430, which has the ability to bond the aluminum plugs to the inside of the carbon fiber tubing. A nice feature of this design is that it allows for experimenters to change the leg lengths of the biped to study the effect that different length thighs and shanks have on the efficiency of walking gaits. It also allows for new leg installations in the case that the leg breaks, as was seen during experiments with Spring Flamingo.

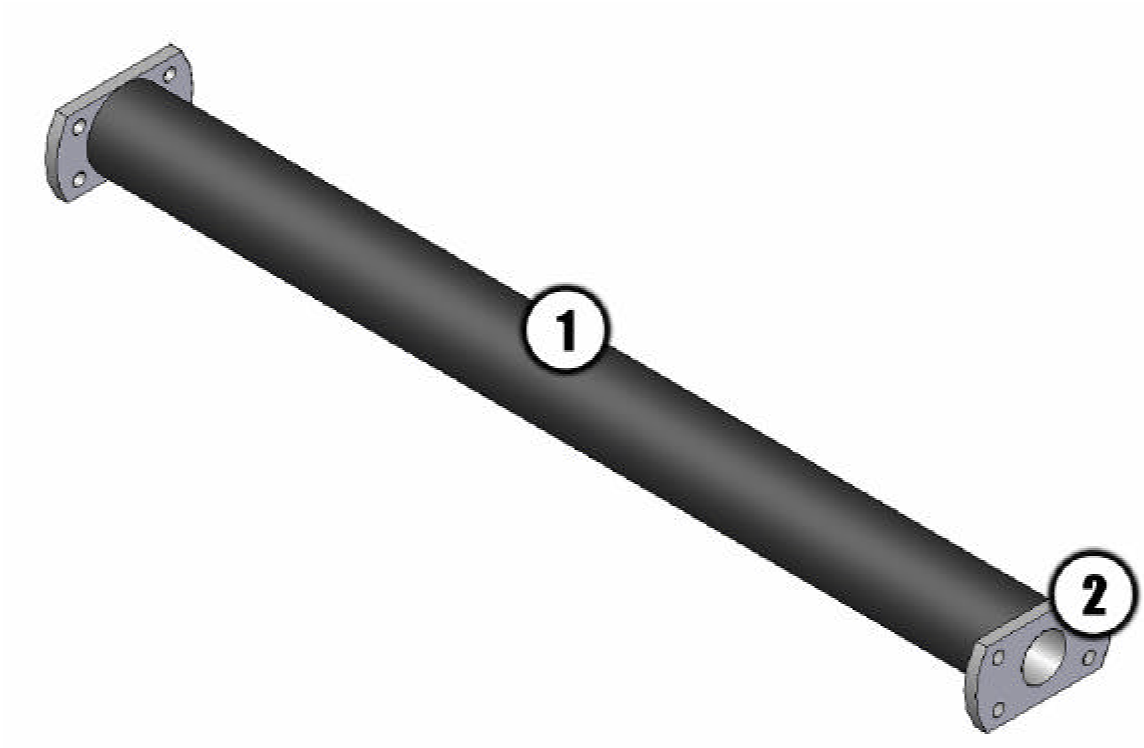


Figure 3.7 Solid model of leg assembly

Table 3.5 Description of numbered items in Fig. 3.7

1: Carbon fiber tubing	2: Leg plug

3.6 Final Design

Based on the solid model developed in SolidEdge, the following design specifications were determined, and the final design can be seen in Fig. 3.8. The height and weight of the final design are 0.97-meters and 12.25-kilograms. Another important set of measurements developed from the solid model, which were used for the control code, are the mass moments of inertia of each limb and the body (see Table 3.6).

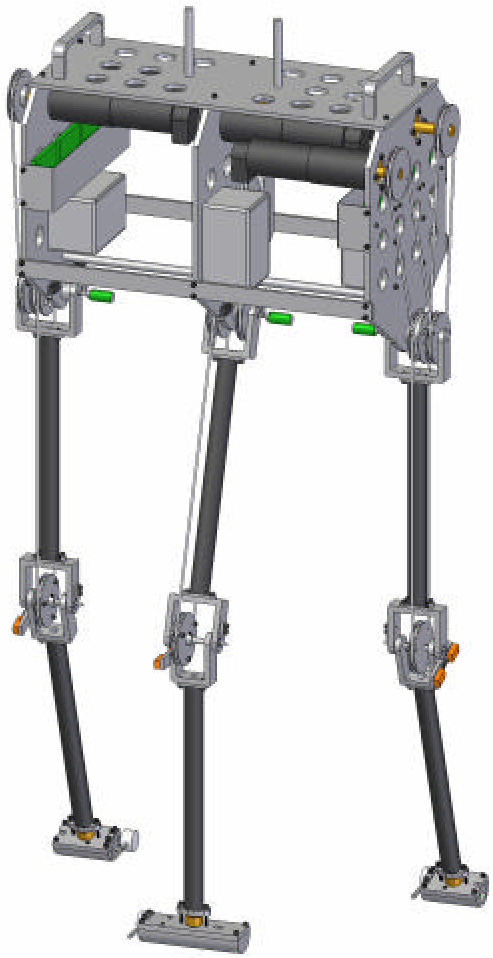


Figure 3.8 Solid model of BIRT

Table 3.6 Physical properties of BIRT

	Mass (kg)	**Moment of Inertia ($kg\text{-}m^2$)**	**Length (m)**
Body	10.30	0.0910	-
Outside Thigh*	0.60	0.0125	0.35
Outside Shank*	0.66	0.0095	0.35
Center Thigh	0.30	0.0062	0.35
Center Shank	0.39	0.0052	0.35

* *Physical properties of these assemblies are combined for both outside legs*

CHAPTER 4

EXPERIMENTAL SETUP

4.1 Platform Cart

The platform cart houses the Opal RT system, three breakout boxes, and power system, see Fig. 4.1. All of these components were mounted to the platform cart for experimental purposes. An umbilical cord runs from the breakout boxes to BIRT, and the cart is useful during experiments where the machine is traversing long distances, rather than having a very long cable.

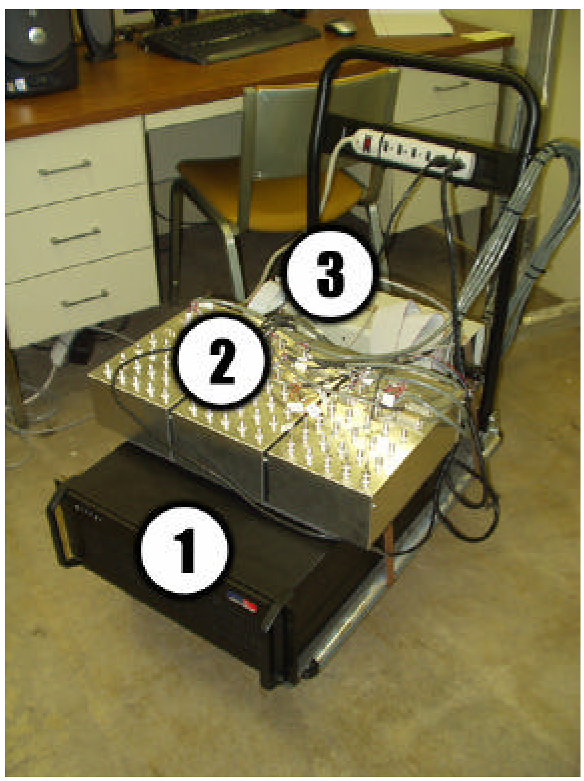


Figure 4.1 Platform cart

1: Opal RT System 2: Breakout Boxes 3: Power System

4.1.1 Opal RT System

The Opal RT system consists of a PC with an Opal RT operating system, which has input and output capabilities. This particular system has three PCI bus cards installed in it. Each card is capable of twenty-four digital I/O channels, sixteen A/D channels, four D/A channels, and six encoder channels. While not all of these channels are used on each card, three cards were needed to supply enough encoder channels.

4.1.2 Breakout Boxes

The breakout boxes were fabricated using off-the-shelf aluminum boxes from Digi-Key. Three identical boxes were fabricated with connections corresponding to the cards installed in the Opal RT PC system. Male BNC connectors were used for the A/D and D/A channels, while twenty-five and nine-pin D-sub connectors were used for the digital I/O and encoder channels, respectively.

4.1.3 Power System

The power system consists of two power supplies and emergency stop circuitry. A 24-volt power supply provides power to the motor amps, while a 5-volt power supply provides power to the load cell amps, limit switches, and emergency stop circuitry. The power system was fabricated using an off-the-shelf steel box purchased from Digi-Key. The top face of the power box also contains a power switch, LED power indicator, and manual emergency stop button.

4.2 Desktop PC

A desktop PC is used to communicate with the Opal RT system. The desktop PC has wireless and wired Ethernet capabilities. Using the desktop PC, the control code is uploaded to and experimental data is downloaded from the Opal RT system.

CHAPTER 5

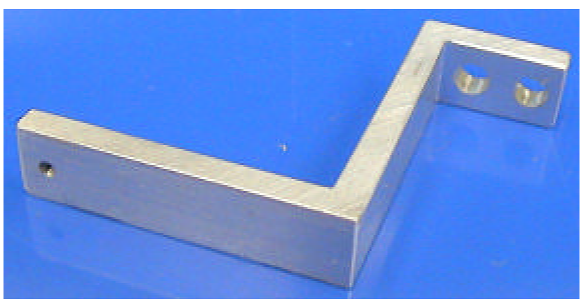
DESIGN COMPLICATIONS

As stated previously, one of the major motivations of this project is to design a walking machine that will serve as a precursor to future biped prototypes to be designed in the Locomotion and Biomechanics Lab at The Ohio State University. For this reason, it is important to include a catalog of design complications encountered during the assembly and operation of this first prototype. All of these complications and current solutions are discussed in detail below.

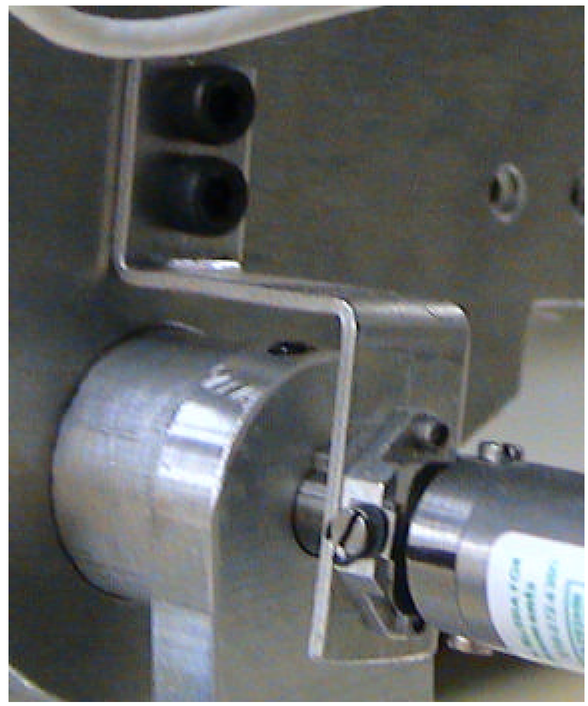
5.1 Encoders

Some initial problems with the encoders were due to the shafts in the feet. The shaft bore in the rotary encoder is 3-mm, and originally, the shafts for these encoders were turned down from readily available larger diameter bar stock. This proved to be problem in the feet, but not in the shafts of the hips and knees, because of their length. Turning down these lengthy and small diameter shafts resulted in bent shafts that did not turn true, and because of this, the encoder would move during each rotation. Eventually, the setscrews fixing the encoder to the shaft would come loose. Purchasing 3-mm stock shafts from McMaster-Carr solved this issue.

Another problem related to the encoders was due to the mounts at the hip and knees, which were manufactured in-house. Originally, these mounts were designed so that the manufacturer's mounts were fastened to the designed mounts using only one mounting hole. However, it eventually became apparent during experiments that this allowed a small amount of play, causing small tracking errors. For this reason, new mounts were designed and fabricated that used both mounting holes of the manufacturer's mounts. Another change that was made to the new encoder mounts was the intended method of fastening the manufacturer's mount to the fabricated mounts. Originally, the fabricated mounts had holes tapped in them for the fasteners. However, the new mounts were designed for a nut instead. The reason for this was due to the fact that one can achieve a larger preload in the mounting fasteners without stripping out the threads of the fabricated aluminum bracket. See Fig. 5.1.



Old mount



New mount

Figure 5.1 Hip encoder mounts

The latest problem encountered concerning the encoders is related to the setscrews that fix the encoder to the shaft. When experiments that involved placing BIRT on the ground and taking assisted steps began, it quickly became apparent that due to the vibrations during ground impact, the setscrews were backing out. This led to the encoders coming loose from the shafts, resulting in poor measurements. Using low-yield-strength Loc-tite solved this problem and this method has been implemented for a couple of months of experiments without seeing similar failures.

5.2 Drive Pulleys

Problems encountered with the drive pulleys result from the method used to fasten them to the drive shafts. Originally, the design called for the drive pulleys and shafts to have keyways machined into them. This was changed, however, during the machining stage of the project to accommodate flats on the shafts. The foreseen advantages to this design change included less machining time and a simpler design. However, this design was not effective, and immediately, a design problem was observed. No matter how much pre-load was placed on the flat of the shaft, there was a significant amount of play in the pulley, which led to poor tracking and control capabilities. For this reason, new drive shafts were fabricated using the original keyway design. Unfortunately, the keyways did not fit snugly on the key-stock, and some play still existed between the drive shafts and pulleys. A final design change was made to rigidly mount the drive pulleys to the U-brackets of the hip and knee joints. This was accomplished by drilling a thru hole in the U-brackets and drive pulleys and fixing the two together using long fasteners. While this solution has solved the problem of play between the drive shafts and pulleys, it has been demonstrated by another prototype produced in the Locomotion and Biomechanics Lab at The Ohio State University [10] that using a keyway is an acceptable means of fixing the drive pulleys to the drive shafts.

A beneficial design change that was made to the prototype involved increasing the diameter of the hole tapped for the setscrew that tightens the cable clamp. For BIRT, a #6-32 UNC setscrew was used for this facet of the drive pulley design. However, the drive pulleys produced for another prototype [10] used a #8-32 UNC setscrew. By increasing the size of the setscrew, a larger Allen wrench could be used, which allowed for more pre-load on the cable clamp, further reducing the possibility of cable slippage.

Another design change to the drive pulleys that may prove beneficial for future applications involves dead-ending the cables within the pulleys. While this possibility was investigated during the design of the drive pulleys, experiments have proven that cable slippage could be a problem while trying to run, where larger cable tensions will be experienced due to higher ground impact forces. For this reason, a design change should be considered on the next prototype.

5.3 Cabling

The cabling purchased from Sava Industries had a nylon coating on it. This coating was found to cause a number of problems. One of the recurring problems during initial experiments was crimp failure. The crimps would fail due to the coating on the cable tearing off allowing the cable to simply slip out of the crimps. By stripping off the cable coating over the crimped sections prior to crimping, this problem was solved.

This same technique was used to solve another problem related to the cable coating. During initial experiments, it was observed that the cables were slipping through the cable clamps of the drive pulleys. Just as with the crimps, the cable coating was tearing off the cable, resulting in cable slippage. By stripping off the cable coating over the clamped sections of the cable, this problem was solved.

As a result of these problems with the nylon cable coating, a design change should be made to future prototypes. It would be beneficial for future prototypes to use cabling that does not have a coating on it. The coating proved to cause numerous problems, however without it the ends of the cable would fray.

5.4 Body Inserts

The design of the body assembly includes body inserts that are press-fit into the body plates and help resist the moment induced on the plates after tensioning the drive cables. During the design of this facet of the body assembly, it was understood that the tension in the cable might cause a large moment on the body plates. However, it was not fully understood how much tension was needed in the drive cables. Based on initial experiments, it was determined that a significant amount of tension was desirable in the drive cables. In fact, so much tension that the outside body plates began to bend and resulted in the legs splaying outwards. Currently, no design changes have been made to account for the leg splay issue because it should not prevent BIRT from walking. However, due to this problem, it is believed that the current design would not be capable of running without bending the outside body plates farther due to a larger ground impact forces and increased cable tension. It is important to realize the need for large cable tensions for future bipeds and design accordingly.

5.5 Feet

During the initial design stages, the clearances for the load cells were based on technical drawings from Sensotec. However, during assembly, it became apparent that the drawings used for design did not correspond to their current load cell model, which resulted in interferences between the fasteners of the foot stabilization system and the perimeter of the load cell. While this was unfortunate, the problem needed to be addressed in order complete assembly, and in the interest of saving time in the fabrication process, a simple modification to the design was made. Since the interference was not extreme, it was possible to simply turn down the threads on the fasteners, see Fig. 5.2. While this solved the interference problem, it introduced a new design problem.

Figure 5.2 Turned down fasteners for feet

With the threads removed on the lower section of the fasteners, there was a certain level of play in the feet, allowing them to rotate approximately ±10°. This was acceptable for initial experiments; however, it was understood that a permanent solution to the problem needed to be made before BIRT could walk. For this reason another design iteration was made by modifying the current leg stabilization system.

The resulting design change included offsetting the fasteners of the foot stabilization system farther from the perimeter of the load cells and is shown in Fig. 5.3. While this design change greatly reduced the amount of play in the feet, it is still not as effective as desired. Regardless, it is effective enough to perform walking experiments.

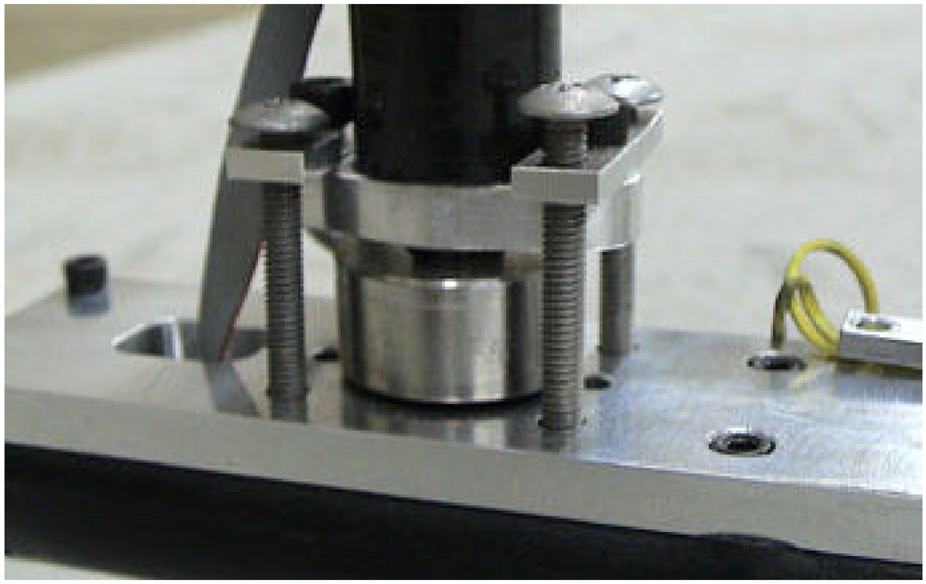


Figure 5.3 Modified foot stabilization system design

Another design change to the feet involved mounting the load cells. The load cell is mounted using two fasteners that extend from the main body of the device. In order to ensure proper foot alignment with the leg the tapped holes, in the leg plug and top plate of the foot, would have to have a precise starting thread location. The original fix for this problem was to use shims under the load cell until the feet were aligned with the shank. Over time however, the shims deteriorated and introduced play in the feet. To account for this problem, the threaded hole of the top footplate was drilled out, and a counter-bore was machined on the bottom side of the footplate to accommodate a nut. The counter-bore was necessary to avoid interferences with the encoders contained in the feet. This design change has proven to be effective thus far during experiments.

Due to the fact that the foot contact is semi-cylindrical and the rotary axis of the foot encoder is not concentric to it, some changes had to be made to the control code. While this facet of the design did not require any changes to the mechanical design, it did need to be accounted for in the control code and is important to make note of for future prototypes.

5.6 Wiring

Wiring is a large part of any actuated biped, and its importance cannot be overlooked during design. A few problems were encountered with the wiring of BIRT. All the connections on BIRT were Molex crimp connections purchased from Digi-Key. The most immediate problem with these connectors was that they contained no means of strain relief, and repeated connections and disconnections led to many of the crimps slipping out of the connectors and the crimps themselves. In order to make the Molex connectors more robust, all replaced crimp connections were soldered to the crimps themselves. While this does not provide a solution to the crimps slipping out of the connector housings, it has eliminated the problem of the wires slipping out of the crimps. One possible way to remedy the strain relief problem involves placing hot-glue in the connector from the backside. While this method has not been implemented on BIRT, it may in the future if this problem persists.

The crimps used for the connections were tin and have introduced some electrical problems. The major problem with using this less expensive crimp material is that the connectors tend to easily oxidize, and the quality of the connection is significantly decreased. As a result, a number of crimp connectors have had to be replaced with new crimps that are not oxidized. It is advised that all crimp connections on future prototypes be gold, which have a superior resistance against corrosion and oxidation. It may also be advantageous to use soldered connections on future prototypes to altogether solve the problems seen with crimps slipping out of connectors and wires slipping out of the crimps.

Originally, all the connectors for the umbilical cable bundle from BIRT to the platform cart were also crimp style connections, just as on BIRT. As mentioned previously, one of the problems associated with this style of connector is their lack of strain relief, and because of this, they were not mounted to BIRT. While methods were found to remedy certain problems with the connectors found on BIRT, it was determined that a more drastic approach needed to be taken in this case. All the original connections were scrapped and replaced with military style Amphenol connectors purchased from Digi-Key. The advantages associated with these connectors are that they have solder connections, strain relief, and can be mounted. Since there was no existing means for mounting the Amphenol connectors to BIRT in the original design, a mounting plate was designed, fabricated and mounted to the top of his body, as shown in Fig. 5.4.

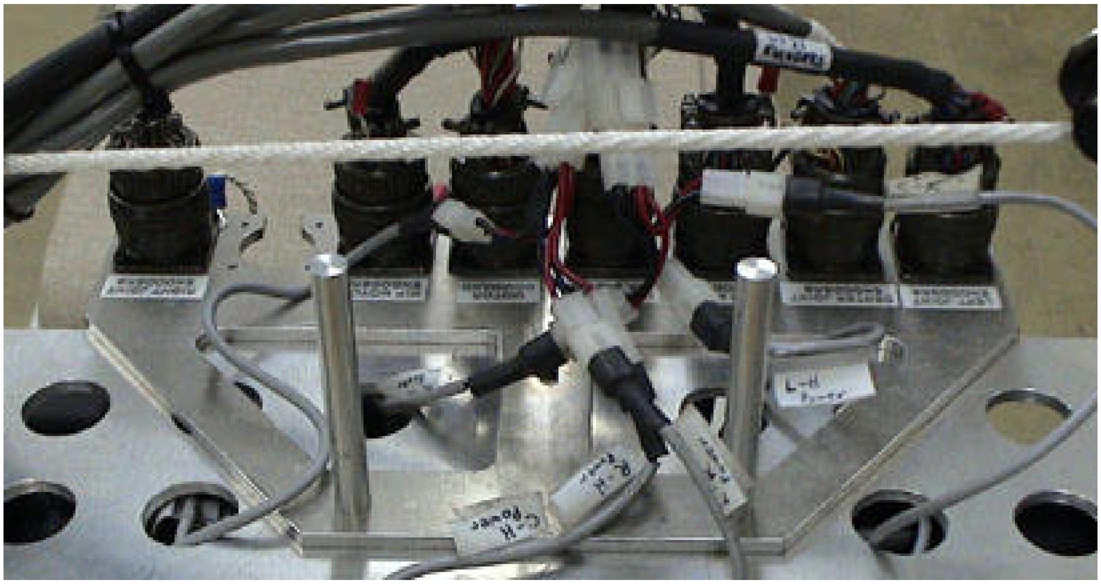


Figure 5.4 Amphenol connector mounting plate

5.7 Opal RT System

Cross-talk is always a concern when dealing with electrical systems, and it was found to be a problem on BIRT. The problem was discovered during experiments when it became apparent that motors that should not have any voltage supplied to them were still being actuated. The solution to this problem was as simple as placing a capacitor across two terminals of the motor amps onboard BIRT, as shown in Fig. 5.5.

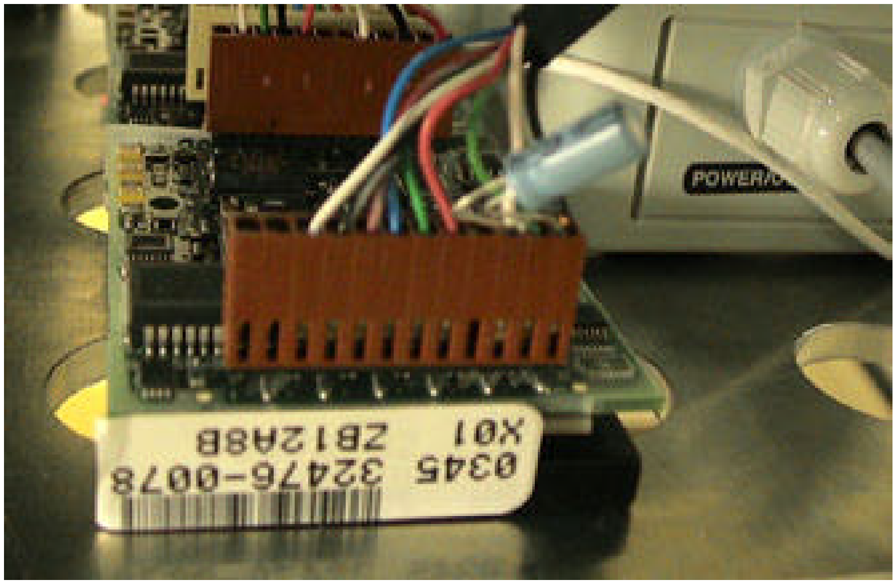


Figure 5.5 Capacitors across motor amps to reduce crosstalk

A more serious problem that was encountered during experiments is related to the D/A channels of the Opal RT system. The problem was that an incorrect command voltage was being sent out of the D/A channels when the Opal system had more than two cards installed in it. While this problem explained a lot of problems that were seen during initial experiments, the remedy was as simple as the makers of the Opal system developing a new driver for the system. The new driver delivered by Opal remedied the problem, and no problems have since been found with the system.

5.8 Motor/Gearhead Selection

The motor and gearhead combination was determined based on simulations, but after a series of experiments, it became apparent that there was not enough torque being supplied by the motors for the center leg. The rated stall current of the motor is six amps; however, the amplifiers are only capable of supplying half that. As a result, we are not able to supply enough current to the motors. This is most obvious at the center hip and knee because while they are the same motors and gearheads used for the outside legs and twice the load needs to be supported by the center leg. Therefore, the center leg suffers the most from the lack of torque. This problem was resolved by replacing the original gearheads of the center hip and knee with one that has a gear reduction of 74:1, resulting in a stall torque of 37.6 N-m.

In this case, the torque problem was solved by simply replacing the gearhead, but the issue demonstrates that while simulations are very useful, one needs to also account for unforeseen discrepancies between simulations and a physical system. For instance, in this case, a significant amount of time would have been lost in the lab to have new body plates machined if it was necessary to increase the size of the motor and gearhead. In future prototype designs, it is important to account for these discrepancies and select a motor and gearhead accordingly.

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